Precision Electroweak Measurements

H.Przysiezniak

CERN, EP Division
1211 Geneva, Switzerland

Abstract. This talk describes some of the precision electroweak measurements from around the world, namely those related to the Z and W bosons, the top quark mass, $\sin^2\theta_{\rm W}$ at NuTeV, and three other fundamental measurements: $\alpha^{-1}(m_{\rm Z}^2)$, $(g-2)_\mu$ at the E821 BNL experiment as well as the atomic parity violation (APV) measurement for the Cesium atom. These and other measurements are set in the context of the Standard Model (SM) and of the electroweak fit predictions. Future prospects for forthcoming experiments are briefly discussed.

INTRODUCTION

The motivations to perform precision electroweak measurements today are as strong as ever. Today's generation of experiments now have data of such precision that the electroweak measurements are probing the quantum corrections to the SM, otherwise known as radiative corrections. These are tested by a wide variety of measurements ranging from the muon magnetic moment to precision measurements at the Z pole and above in e^+e^- collisions, as well as precision measurements at hadron colliders. This talk is not an exhaustive survey but rather a biased summary of recent and new results, in particular: those which have an influence on the indirect determination of the Higgs mass, and those which are devised to be extremely stringent tests of the SM.

The measurements that are described here and which enter the first category are: the Z line shape and branching ratio measurements as well as the Z peak asymmetries from which $\sin^2\theta^\ell_{\rm eff}$ is extracted, the W mass, the top quark mass, $\sin^2\theta_{\rm W} = 1 - m_{\rm W}^2/m_{\rm Z}^2$ at NuTeV and $\alpha^{-1}(m_{\rm Z}^2)$. The relation between the electroweak quantities are affected by radiative corrections. The most precisely known quantities being $\alpha(m_{\rm Z}^2)$, G_F and $m_{\rm Z}^2$, the W mass is related to them as follows

$$m_{\rm W}^2 = \frac{\pi\alpha(m_{\rm Z}^2)}{\sqrt{2}G_F(1-m_{\rm W}^2/m_{\rm Z}^2)(1-\Delta r^{\rm ew})}$$

and the effective weak mixing angle, $\sin^2\theta^\ell_{\rm eff} = (1/4)(1 - g^\ell_V/g^\ell_A)$, by the relation

$$\sin^2\theta^\ell_{\rm eff}\cos^2\theta^\ell_{\rm eff} = \frac{\pi\alpha(m^2_{\rm Z})}{\sqrt{2}G_F m^2_{\rm Z}(1+\epsilon_1)(1-\epsilon_3/\cos^2\theta_{\rm W})}, \tag{1}$$

where ϵ_1, ϵ_3 and $\Delta r^{\rm ew} = f(\epsilon_1,\epsilon_2,\epsilon_3)$ are the radiative corrections. They are functions of $m^2_{\rm top}$ and of $\log(m_{\rm Higgs}/m_{\rm Z})$. The W mass and effective weak mixing angle measurements help to constrain the yet unobserved Higgs mass. Still, it can be deduced from the above expressions that reducing the error on $\sin^2\theta^\ell_{\rm eff}$ will constrain $m_{\rm Higgs}$ even more particularly if the error on $\alpha(m^2_{\rm Z})$ is reduced simultaneously. The same relationship exists between the W mass and the top quark mass: reducing the experimental errors simultaneously will help to constrain the Higgs mass better.

The measurements which enter the second category are: the Z measurements from which Universality tests are performed, fermion pair production and asymmetries from the LEPII $\rm e^+e^-$ collider above the Z pole, W production and decays, gauge boson self-interactions and atomic parity violation. These measurements stringently test family Universality, Universality of weak neutral and charged current couplings, symmetry breaking and radiative corrections.

Z BEST OF BOTH WORLDS

The measurements described in the following sections were made at e^+e^- colliders: at SLC using the SLD detector, and at LEP using the ALEPH, DELPHI, L3 and OPAL detectors, at the Z pole and above in the case of LEPII. Approximately 4×10^6 Zs were accumulated per LEP experiment, while 555k Zs were taken at SLD using a polarized electron beam. The measurements help to constrain the Higgs mass and serve as stringent tests of the SM. The Z electroweak observables (at the Z peak, after QED corrections) are

- Line Shape: $m_{\rm Z}$, $\Gamma_{\rm Z}$, $\sigma^0_{\rm h} = 12\pi\Gamma_{\rm ee}\Gamma_{\rm had}/(m^2_{\rm Z}\Gamma^2_{\rm Z})$
- Branching Ratios: $R_\ell = \Gamma_{\rm had}/\Gamma_\ell$, $R_{\rm b} = \Gamma_{\rm b\bar{b}}/\Gamma_{\rm had}$ and $R_{\rm c} = \Gamma_{\rm c\bar{c}}/\Gamma_{\rm had}$
- Unpolarized FB Asymmetries for $f = \ell, {\rm b}, {\rm c}$: $A^f_{FB} = \frac{\sigma^f_F - \sigma^f_B}{\sigma^f_F + \sigma^f_B} = 0.75 A_{\rm e} A_{\rm f}$
- Polarization of τ leptons:

$$\mathcal{P}_\tau(\cos\theta) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{A_\tau(1+\cos^2\theta) + 2A_{\rm e}\cos\theta}{1+\cos^2\theta + 2A_\tau A_{\rm e}\cos\theta}$$

- Left-Right Asymmetry:

$$A^m_{LR} = \frac{\sigma^f(-|\mathcal{P}_{\rm e}|) - \sigma^f(+|\mathcal{P}_{\rm e}|)}{\sigma^f(-|\mathcal{P}_{\rm e}|) + \sigma^f(+|\mathcal{P}_{\rm e}|)} = \mathcal{P}_{\rm e} A^0_{LR} = \mathcal{P}_{\rm e} A_{\rm e} \quad f \neq e$$

- Left-Right FB Asymmetries for $f = \ell, {\rm b}, {\rm c}, {\rm s}$:

$$A^{\rm pol}_{\rm FB} = \frac{\sigma^f_F(-|\mathcal{P}_{\rm e}|) - \sigma^f_B(-|\mathcal{P}_{\rm e}|) - \sigma^f_F(+|\mathcal{P}_{\rm e}|) + \sigma^f_B(+|\mathcal{P}_{\rm e}|)}{\sigma^f_F(-|\mathcal{P}_{\rm e}|) + \sigma^f_B(-|\mathcal{P}_{\rm e}|) + \sigma^f_F(+|\mathcal{P}_{\rm e}|) + \sigma^f_B(+|\mathcal{P}_{\rm e}|)} = 0.75\mathcal{P}_{\rm e} A_{\rm f}$$

Z Resonance Parameters at LEP

The Z resonance parameters (m_Z, Γ_Z, σ^0_h and R_ℓ) are measured at LEP using $\mathrm{q\bar{q}}$ and $\ell^+\ell^-$ event samples collected during scans of the Z peak. Since the lepton asymmetries A^ℓ_FB are sensitive functions of $\sqrt{s}$, they are also extracted from a simultaneous fit to the $\mathrm{q\bar{q}}$ and $\ell^+\ell^-$ lineshape data. The SM values are used for the $\mathrm{Z}\gamma$ and γ cross sections and the radiatively corrected lineshape functions are fit to data.

Combining the results from the four LEP experiments and for all years, assuming lepton Universality []: $m_\mathrm{Z} = 91.1871 \pm .0021$ (.0017syst) (SM: 91.18692) GeV, $\Gamma_\mathrm{Z} = 2.4944 \pm .0024$ (.0013syst) (SM: 2.49589) GeV, $\sigma^0_h = 41.544 \pm .037$ (.035syst) (SM: 41.4804) nb, $R_\ell = 20.768 \pm .024$ (.017syst) (SM: 20.7394), $A^{0,\ell}_\mathrm{FB} = .01701 \pm .00095$ (.00060syst) (SM: .016342).

The dominant sources of systematic uncertainties are the normalization of the cross sections, the knowledge of the center-of-mass energy $\mathrm{E_{cm}}$ and the QED radiative corrections to the line shape function.

Left-Right Asymmetry at SLD

This is a powerful, almost systematic free measurement made using a polarized electron beam ($\mathcal{P}_\mathrm{e}$=22% in 1992; 63% in 1993; 73 to 78% from 1994 to 1997). The helicity of the polarized electrons is changed pulse to pulse. A feedback system keeps the left and right-handed electron currents equal to 10^{-4}. The left and right-handed luminosities are equal to very good approximation. The asymmetry is defined as $A^0_\mathrm{LR} = (1/\mathcal{P}_\mathrm{e})[N_\mathrm{Z}(\mathrm{L}) - N_\mathrm{Z}(\mathrm{R})]/[N_\mathrm{Z}(\mathrm{L}) + N_\mathrm{Z}(\mathrm{R})] = A_\mathrm{e}$ where $N_\mathrm{Z}(\mathrm{L,R})$ are the number of hadronically decaying Zs counted with left and right-handed electron beams. A_e is a function of $\sin^2\theta^\ell$: $A_\mathrm{e} = [2(1-4\sin^2\theta^\ell_\mathrm{eff})]/[1+(1-4\sin^2\theta^\ell_\mathrm{eff})^2]$, such that the A_LR measurement is translated into an effective weak mixing angle measurement []

$$A_\mathrm{LR} = .15108 \pm .00218 \rightarrow \sin^2\theta^\ell_\mathrm{eff} = .23101 \pm .00028\ (.00018\mathrm{syst})\ (\mathrm{SM:}\ \ .23145).$$

The dominant sources of systematic uncertainties are the electron polarization and the center-of-mass energy. As a cross check, the polarization of the positron beam was measured, and it was found to be consistent with zero: $\mathcal{P}_{\mathrm{e}^+} = -.02 \pm .07\%$.

Z Summed Up

The lineshape parameters are used to extract the partial decay widths []: not assuming lepton Universality $\Gamma_\mathrm{ee} = 83.90 \pm .12$ MeV, $\Gamma_{\mu\mu} = 83.96 \pm .18$ MeV, $\Gamma_{\tau\tau} = 84.05 \pm .22$ MeV; assuming lepton Universality $\Gamma_{\ell\ell} = 83.96 \pm .09$ MeV, $\Gamma_\mathrm{had} = 1743.9 \pm 2.0$ MeV, $\Gamma_\mathrm{invisible} = 498.8 \pm 1.5$ MeV. Taking the measured value for $\Gamma_\mathrm{invisible}/\Gamma_{\ell\ell} = 5.941 \pm .016$ and dividing it by the SM expectation for $\Gamma_{\nu\nu}/\Gamma_{\ell\ell} =$

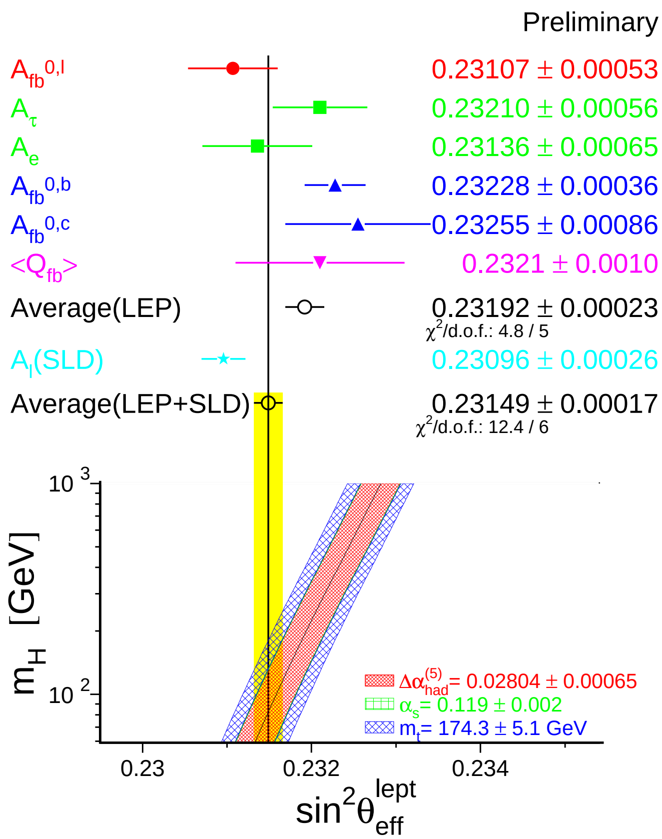

FIGURE 1. Summary of the LEP and SLD asymmetry measurements which enter in the determination of the world average effective weak mixing angle.

$1.9912 \pm .0012$, the number of neutrino families is extracted: $N_\nu = 2.9835 \pm .0083$. Converted into a 95% C.L. upper limit on an additional invisible width assuming $N_\nu = 3$ gives $\Delta\Gamma_{\text{invisible}} < 2.0$ MeV.

From the leptonic widths $\Gamma_{\ell\ell} = (1+3\alpha/4\pi)(G_F m_Z^3/24\pi\sqrt{2})[1+(g_V^\ell/g_A^\ell)^2](1+\epsilon_1)$ and asymmetries $A_\ell = 2g_V^\ell g_A^\ell/(g_V^{\ell\,2} + g_A^{\ell\,2})$, the vector and axial vector coupling ratios are determined []: $g_A^\mu/g_A^e = 1.0001 \pm .0014$, $g_V^\mu/g_V^e = 0.981 \pm .082$, $g_A^\tau/g_A^e = 1.0019 \pm .0015$ and $g_V^\tau/g_V^e = 0.964 \pm .032$, consistent with Universality of the leptonic weak neutral couplings.

The effective weak mixing angle $\sin^2\theta_{\text{eff}}^\ell$ is extracted from the SLD and LEP Z-pole leptonic asymmetries. The asymmetries entering the world average (LEP+SLD) effective weak mixing angle determination are presented in Figure 1 []. The LEP quark asymmetry measurement $A_{fb}^{0,b}$ and the SLD leptonic asymmetry A_ℓ differ by $\sim 3\sigma$. This discrepency remains unresolved: possibly a statistical fluctuation, or an unkown systematic effect, or new physics. Nonetheless. $\sin^2\theta_{\text{eff}}^\ell$ remains the strongest constraint on the Higgs mass today.

Fermion Pair Production and Asymmetries at LEPII

Fermion pairs are produced through the radiative return diagram, when an initial state photon is emitted and the effective center-of-mass energy $\sqrt{s'}$ is approximately equal to the Z mass, and through the non-radiative diagram, when $\sqrt{s'/s} > 0.85$. The cross section and asymmetries are determined for these non-radiative events. From these measurements, limits on a wide range of physics scenarios can be set.

For example, the cross sections and asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states can be used to set limits on contact interactions between leptons expected to occur in the presence of composite fermions. These interactions are parametrised by an effective Lagrangian which is added to the SM one: $\mathcal{L}_{\rm eff} = [g^2\eta/(1+\delta)\Lambda^2]\sum_{i,j=L,R}\eta_{ij}[\bar{\rm e}_i\gamma_\mu {\rm e}_i][\bar{\rm f}_j\gamma^\mu {\rm f}_j]$, where $g^2/4\pi = 1$ by convention, $\eta = \pm$ defines a constructive or destructive interference with the SM, $\delta = 1(0)$ for $\rm f = e(f \neq e)$, $\eta_{ij} = \pm 1, 0$ is the helicity coupling between initial and final state, $\rm e_{L,R}$, $\rm f_{L,R}$ are the left and right-handed spinors, and Λ is the scale of the contact interactions.

For all LEP results combined, the excluded values of Λ for models leading to large deviations in $\mu^+\mu^-$ and $\tau^+\tau^-$ final states are []: $\Lambda^{(+,-)}_{\rm AA} < (17.6, 13.9)$, $\Lambda^{(+,-)}_{\rm VV} < (20.4, 17.2)$, $\Lambda^{(+,-)}_{\rm RR} < (12.3, 9.7)$ and $\Lambda^{(+,-)}_{\rm LL} < (12.8, 10.2)$ TeV, where $\eta_{LL} = 1, 1, 0, 1$, $\eta_{RR} = 1, 1, 1, 0$, $\eta_{LR} = -1, 1, 0, 0$ and $\eta_{RL} = -1, 1, 0, 0$ for the AA, VV, RR and LL models respectively.

W BOSONS ON TOUR

W boson related measurements were performed by the UA1 and UA2 experiments at the SPS collider ($\rm p\bar{p}$, $E_{cm} = 630$ GeV, $\mathcal{L}_{\rm int} \sim 12{\rm pb}^{-1}$/expt.), at the Tevatron by the CDF and D0 experiments ($\rm p\bar{p}$, $E_{cm} = 1.8$ TeV, $\mathcal{L}_{\rm int} \sim 120{\rm pb}^{-1}$/expt.), and at LEPII ($\rm e^+e^-$, $E_{cm} = 161 \rightarrow 209$ GeV, $\mathcal{L}_{\rm int} > 500{\rm pb}^{-1}$/expt.). The W electroweak observables described here are: the W production and decays, the gauge boson self interactions and the W mass and width. These observables help to constrain the Higgs mass or serve as stringent tests of the SM.

W Pair Production and Decays at LEPII

W pairs are produced via the t-channel neutrino exchange and via the s-channel $\gamma - \rm Z$ interference. The cross section is measured by the four LEP experiments for all decay channels: the fully hadronic channel (4q; BR$\sim$46%), the semileptonic channel ($\ell\nu\rm q\bar{q}$; BR$\sim$43%), and the fully leptonic channel ($\ell\nu\ell\nu$; BR$\sim$11%). The combined measurements are shown in Figure 2 as a function of the center-of-mass energy []. The curves correspond to three calculations of the cross section: the two lower curve calculations (top:YSFWW3; bottom:RacoonWW) contain non leading $\mathcal{O}(\alpha)$ terms, whereas the upper curve calculation (Gentle) does not. The χ^2/dof for data versus Gentle is 11.6/6, whereas that of data versus Racoon is 5.6/6.

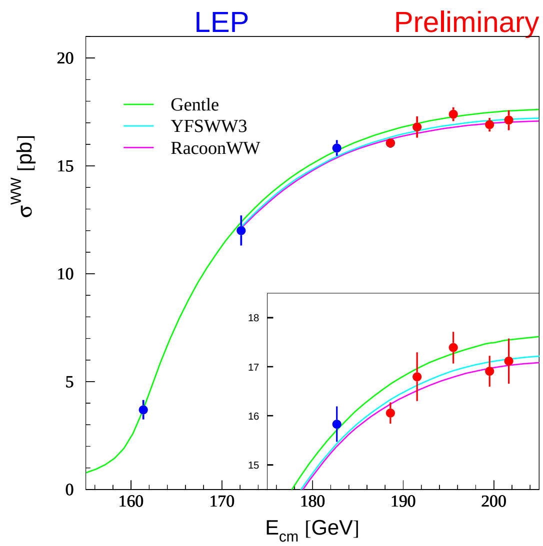

FIGURE 2. LEPII WW cross section as a function of the center-of-mass energy. The points are the data, the curves are the calculations from Gentle (top curve), YSFWW3 (middle) RacoonWW(bottom).

The branching ratio measurements from LEPII and the Tevatron BR($W \rightarrow e\nu$) measurement are consistent with Universality of the leptonic weak charged current []: BR($W \rightarrow e\nu$) $= 10.63 \pm 0.20\%$, BR($W \rightarrow e\nu$)(Tevatron) $= 10.43 \pm 0.25\%$, BR($W \rightarrow \mu\nu$) $= 10.56 \pm 0.19\%$, BR($W \rightarrow \tau\nu$) $= 11.02 \pm 0.26\%$. The result from LEPII assuming lepton Universality is given by: BR($W \rightarrow \ell\nu$) $= 10.71 \pm 0.10\%$, BR($W \rightarrow q\bar{q}$) $= 67.85 \pm 0.33\%$.

Using the measured hadronic branching ratio, the following relation

$$\frac{\mathrm{BR}_{W\rightarrow qq}}{1-\mathrm{BR}_{W\rightarrow qq}} = (|V_{ud}|^2 + |V_{cd}|^2 + |V_{us}|^2 + |V_{cs}|^2 + |V_{ub}|^2 + |V_{cb}|^2)(1 + \frac{\alpha_s(m_W^2)}{\pi})$$

and the known values of the other CKM matrix elements, one finds $|V_{cs}| = .993 \pm .016$ []. This improves by a factor of ten the precision of the PDG value, which is also obtained without requiring Unitarity of the CKM matrix.

Gauge Boson Self Interactions

Any deviation from the SM prediction for gauge boson self-interactions is a true indication of non-SM physics and could indicate W compositeness. Triply charged (TGC), neutral or quartic gauge couplings have been investigated. Only the TGCs are discussed here. The general Lagrangian for TGCs contains 14 parameters. By requiring C, P and CP invariance and $U(1)_{em}$ invariance ($q_W = e$), 5 free parameters are left. Measurements made at LEP at the Z pole set bounds on the

couplings. Finally, by requiring the additional $\mathrm{SU(2)_L \times U(1)_Y}$ invariance, three couplings are left: κ_γ, g_1^{Z} and λ_γ where the SM predictions are 1, 1, 0. g_1^{Z} is the coupling strength of the W to the Z. κ_γ and λ_γ define the magnetic moment and the electric quadrupole moment of the W^+: $\mu_{\mathrm{W}^+} = (\mathrm{e}/2m_{\mathrm{W}})(1+\kappa_\gamma+\lambda_\gamma)$ and $Q_{\mathrm{W}^+} = -(\mathrm{e}/m_{\mathrm{W}}^2)(\kappa_\gamma - \lambda_\gamma)$.

At Tevatron

Limits on TGCs are set by looking at the $p_T^{\ell\nu}$ distribution of $\mathrm{WW}, \mathrm{WZ} \rightarrow (\mathrm{e},\mu) + \nu +$ jets events (λ,κ), the cross section of $\mathrm{WZ} \rightarrow (\mathrm{e},\mu) + \nu + \mathrm{ee}$ events (λ, g_1), the p_T^{ℓ} distribution of WW $\rightarrow$ dileptons events (λ,κ), and the E_T^{γ} distribution of $\mathrm{W}\gamma \rightarrow (\mathrm{e},\mu) + \nu + \gamma$ events (λ,κ). Any excess of events is an indication for anomalous TGCs. Since the cross section with non-SM couplings increases with s, to avoid Unitarity violation, the anomalous couplings are expressed as form factors with a scale Λ e.g. $\lambda_V(s) = \lambda_V/(1+s/\Lambda^2)^2$. Under the assumption that the $\mathrm{WW}\gamma$ couplings equal the WWZ couplings, for $\Lambda = 2.0$ TeV, the one dimensional 95% C.L. limits are $\Delta\kappa_\gamma = (-0.25, 0.39)$ and $\lambda_\gamma = (-0.18, 0.19)$ [], where Δ indicates the deviation with respect to the SM prediction. Assuming the $\mathrm{WW}\gamma$ couplings are at the SM value, for $\Lambda = 2.0$ TeV, the one dimensional 95% C.L. limit is $\Delta g_1^{\mathrm{Z}} = (-0.37, 0.57)$ [].

At LEPII

Limits on TGCs are set through measurements of the cross section and W production and decay angles for WW events (κ, g_1, λ), and through measurements of the cross section, energy and θ of the lepton, jets or γ, for single W or single γ events (κ,λ). The largest sensitivity comes from the measurement of the W production and decay angles for WW events decaying semileptonically. The one dimensional 95% C.L. limits for the four LEP experiments combined are $\Delta\kappa_\gamma = (-0.09, 0.15)$, $\Delta g_1^{\mathrm{Z}} = (-0.071, 0.024)$ and $\lambda_\gamma = (-0.066, 0.035)$ [].

W Mass and Width

At Tevatron

Single Ws are produced in $\mathrm{q\bar{q}}$ annihilations of the proton and anti-proton valence quarks. The W hadronic decays are lost in the QCD di-jet background and thus only leptonic decays are used for the measurement. The longitudinal information is lost at large η due to high background and lack of instrumentation, such that transverse quantities are used to determine the W mass. Two complementary variables are the transverse mass $m_T = \sqrt{2p_T^{\ell} \not{E}_T(1-\cos\phi_{\vec{\not{E}}_T - \vec{p}_T^{\ell}})}$ and the transverse

momentum of the lepton p_T^ℓ. m_T and p_T^ℓ are respectively, to first order independent and linearly dependent, of p_T^{W}. They are less-more sensitive to the W production process, and more-less sensitive to detector resolutions. A Monte Carlo (MC) simulation of the W production, decay and detector response is used to generate the m_T and p_T^ℓ distributions as a function of m_{W}^{true}. Today's Tevatron W mass is $m_{\mathrm{W}} = 80.450 \pm .063$ (.040stat; .049syst) GeV (CDF: $80.433 \pm .079$; D0: $80.474 \pm .093$) []. The W width is extracted from a fit to the high end of the m_T distribution by CDF $\Gamma_{\mathrm{W}} = 2.06 \pm .13$ GeV [].

The main systematics originate from the uncertainty on the energy response and resolution, and on the p_T and $\not{E}_T$ MC modelling. Since Z events are needed to set the energy-momentum scales and the W p_T and $\not{E}_T$ models, the systematic uncertainties are dominated by the limited Z statistics.

At LEPII

The W mass can be extracted via three different methods at LEPII. The first is a measurement of the W pair production cross section at the threshold center-of-mass energy (161 GeV). At this energy, the cross section is most sensitive to the W mass.

In the second method, the lepton energy spectrum of the fully leptonic or semileptonic events is measured: its endpoints are a function of the W mass $E_{\pm}^{\ell} = (\sqrt{s}/4)(1 \pm \sqrt{1 - 4m_{\mathrm{W}}^2/s})$.

Finally, the direct reconstruction is the third and most powerful method. Only the fully leptonic events are not used here because they are underconstrained and the invariant mass of the Ws cannot be unambiguously determined. The center-of-mass energy is known very precisely and acts as a very strong constraint. The invariant mass is determined using a five or two constraint kinematic fit, for 4q or semileptonic events respectively. In addition, the 4q events require a jet pairing algorithm to determine which jets correspond to which W. Bad pairings bring about combinatorial background and contain little or no information on the W mass. A convolution or binned likelihood method is used to extract the W mass from the invariant mass distribution. Combining the direct reconstruction results from the four LEP experiments gives $m_{\mathrm{W}} = 80.401 \pm .048$ (.027stat; .040syst) GeV (Aleph: $80.449 \pm .065$; Delphi: $80.308 \pm .090$; L3: $80.353 \pm .088$; Opal: $80.446 \pm .065$) []. The W width and mass are extracted simultaneously in a two dimensional fit and the LEP combined result for the width is $\Gamma_{\mathrm{W}} = 2.19 \pm .15$ GeV []. The main systematics originate from the uncertainties on the LEP center-of-mass energy (17 MeV), the final state interactions (18 MeV), and the fragmentation (28 MeV).

Combining all results from all methods at LEPII with the Tevatron and UA2 results, the world average is given by []

$$m_{\mathrm{W}}^{\mathrm{WA}} = 80.419 \pm .038 \text{ GeV}.$$

TOP MASS AT TEVATRON

The top quark was discovered at Tevatron in 1995. Its mass is measured with a precision of 3% and makes it the most precisely known quark mass. The top mass measurement strongly constrains the Higgs mass, since the radiative corrections are functions of both of these parameters.

Top quark pairs are produced through $q\bar{q}$ annihilation into a gluon which splits into a $t\bar{t}$ pair. The gluon is not a colour singlet, such that colour strings are allowed to form between the top and the anti-top. This colour crosstalk is difficult to model and is one of the main sources of systematic uncertainties. The top (anti-top) then decays almost exclusively into a b (anti-b) quark and a W boson, and the W decays either hadronically or leptonically.

The combined CDF and D0 error on the top mass for the all hadronic channel, when both Ws decay hadronically (BR∼44%, Signal/Noise∼1/4), is approximately 8.5 (7*stat*) GeV. The invariant mass of the top decay products is determined in a three constraint kinematic fit. The di-lepton channel (BR∼5%, S/N∼4) has approximately the same precision and statistical weight. The events are under-constrained such that no invariant mass can be calculated. In this case, the decay dynamics of the data is compared with the MC expectation e.g. using the p_ν distribution. The top mass determined from the lepton+jet channel (BR∼30%, S/N∼1) has an error of ∼ 5.5 (4*stat*) GeV, corresponding to a statistical weight of ∼80% in the average. A two constraint kinematic fit is used to determine the invariant mass of the top quark decay products. The Tevatron top mass, for all channels and for CDF and D0 combined, is []

$$m_{\rm top} = 174.3 \pm 5.1 \ (3.2{\rm stat}; 4.0{\rm syst}) \ {\rm GeV}$$

with CDF: 176.0 ± 6.5 GeV and D0: 172.1 ± 7.1 GeV. The main systematics originate from the uncertainties on the jet energy scale, and on the MC modelling of the QCD effects.

$\sin^2\theta_{\rm W}$ AT NUTEV

The weak mixing angle has been measured by CCFR and more recently by NuTeV, at Fermilab. Early determinations of $\sin^2\theta_{\rm W}$ gave the SM's successful prediction of $m_{\rm W}$ and $m_{\rm Z}$. More precise measurements gave the first useful limits on the top quark mass. The most recent results are the most precise to date and help to constrain the Higgs mass.

The Lewellyn Smith relation $\rm R^\nu = NC/CC = f(\sin^2\theta_W, \chi)$ can be used to extract $\sin^2\theta_{\rm W}$. NC (CC) is the number of neutral (charged) current events, and χ is the effect of the sea quark scattering e.g. the charm quark mass. Unfortunately, χ is the largest source of systematic uncertainties. NuTeV rather uses the Paschos Wolfenstein relation $\rm R^- = (NC^\nu - NC^{\bar\nu})/(CC^\nu - CC^{\bar\nu}) = (R^\nu - rR^{\bar\nu})/(1-r) = 1/2 - \sin^2\theta_W$ where $\rm r = CC^{\bar\nu}/CC^\nu$. Using this relation, almost all sensitivity to

χ cancels out but separate ν and $\bar{\nu}$ beams are needed. These are supplied by the FNAL sign selected quadrupole train which selects mesons of the appropriate sign. Contamination of the beams remains small: <1/1000 (<1/500) of $\bar{\nu}_\mu$ (ν_μ) in the ν_μ ($\bar{\nu}_\mu$) beam; 1.3% (1.1%) of ν_{e} in the ν_μ ($\bar{\nu}_\mu$) beam.

The NC and CC events are characterized by their event length: CCs produce long event length muons, whereas NCs produce short hadronic showers. For ν and $\bar{\nu}$ separately, NuTeV measures $\mathrm{R}^{\mathrm{meas}}_{\nu(\bar{\nu})}$ = [# short evts in $\nu_\mu(\bar{\nu}_\mu)$ mode]/ [# long evts in $\nu_\mu(\bar{\nu}_\mu)$ mode]. $\mathrm{R}^{\nu}_{\mathrm{MC}}$ and $\mathrm{R}^{\bar{\nu}}_{\mathrm{MC}}$ are both functions of $\sin^2\theta_{\mathrm{W}}$ and χ. The relation $\tilde{\mathrm{R}}^- = \mathrm{R}^\nu - \mathrm{x}\mathrm{R}^{\bar{\nu}}$ is minimized with respect to χ, giving $x = .5136$. $\sin^2\theta_{\mathrm{W}}$ is then varied until $\tilde{\mathrm{R}}_{\mathrm{MC}} = \tilde{\mathrm{R}}_{\mathrm{data}}$. For $m_{\mathrm{top}} = 175$ GeV and $m_{\mathrm{Higgs}} = 150$ GeV []

$$\sin^2\theta_{\mathrm{W}} = 1 - m^2_{\mathrm{W}}/m^2_{\mathrm{Z}} = .2253 \pm .0021\ (.0018\mathrm{stat}; .0010\mathrm{syst})\ (\mathrm{SM}:\ .2227)$$

with residual dependence on m_{top} and m_{Higgs}: $\delta\sin^2\theta_{\mathrm{W}} = -.00435[(m_{\mathrm{t}}/175)^2 - 1] + .00048\log(m_{\mathrm{H}}/150)$ with m_{t} and $\mathrm{m_H}$ in GeV. This translates into a value of the W mass: $m_{\mathrm{W}} = 80.26 \pm .11$ GeV.

EXTRA BEAUTIFUL MEASUREMENTS

A precise determination of $\alpha(m^2_{\mathrm{Z}})$ becomes extremely important in the context of the electroweak fits. From Equation 1, one can deduce that the size of $\Delta\alpha(m^2_{\mathrm{Z}})$ limits the precision on $\log m_{\mathrm{H}}$ via the radiative corrections ϵ_1 and ϵ_3.

A precise measurement of the muon magnetic moment is also of great importance. The relation between the μ magnetic moment and the spin is given by $\vec{\mu} = g(\mathrm{e}/m)\vec{s}$. Radiative corrections bring deviations from $g = 2$, defined as $a_\mu = (g-2)/2$, but these could also originate from non-SM effects.

Thirdly, the Cesium atomic parity violation measurement is discussed.

In the case of $\alpha^{-1}(m^2_{\mathrm{Z}})$

The electromagnetic constant at center-of-mass energy $\sqrt{s}$ can be written as [] $\alpha(s) = \alpha(0)/[1 - \Delta\alpha_{\mathrm{lept}}(s) - \Delta\alpha_{\mathrm{had}}(s)]$. The leptonic contribution is precisely calculated to three loop order: $\Delta\alpha_{\mathrm{lept}}(m^2_{\mathrm{Z}}) = 314.97686 \times 10^{-4}$. The hadronic vacuum polarization term has the largest uncertainty and is determined via a dispersion integral: $\Delta\alpha_{\mathrm{had}}(m^2_{\mathrm{Z}}) = -[\alpha(0)m^2_{\mathrm{Z}}/3\pi] \cdot Re\int^{\infty}_{4m^2_\pi} ds\{R(s)/[s(s-m^2_{\mathrm{Z}}) - i\epsilon]\}$, where $R(s) = \sigma_{\mathrm{ee}\to\mathrm{had}}/\sigma_{\mathrm{ee}\to\mu^+\mu^-}$. $R(s)$ is measured from $\mathrm{e^+e^-} \to$ hadron data for $\sqrt{s} < 40$ GeV, and is evaluated using perturbative QCD (PQCD) for $\sqrt{s} > 40$ GeV, giving $\Delta\alpha_{\mathrm{had}} = (280 \pm 7) \times 10^{-4}$. Summing these results, one obtains $\alpha^{-1}(m^2_{\mathrm{Z}}) = 128.902 \pm .090$, which in today's electroweak fits translates into $\Delta\log m_{\mathrm{H}} = \pm.30$.

However, it is possible to reduce the error on $\Delta\alpha_{\mathrm{had}}$ by taking more data at $\sqrt{s} = 0.3 - 5.0$ GeV, by using PQCD down to $\sqrt{s} = 1.8$ GeV and by applying

theory constraints from QCD sum rules []. These steps should bring the error down to $\Delta\alpha^{-1} = \pm.02$, which would translate into $\Delta \log m_{\mathrm{H}} = \pm.20$.

$\mathrm{e^+e^-} \rightarrow$ hadron data are presently being taken by various experiments, in particular by BESII in China ($2 < \sqrt{s} < 5$ GeV), and by CMD-2 and SND in Novosibirsk ($0.6 < \sqrt{s} < 1.4$ GeV). The first run of BESII in 1998 has brought the error on $R(s)$ from 15-20% down to 7% []. Combining the Novosibirsk and BESII data, a 1999 preliminary evaluation has given $\Delta\alpha^{-1}(m_{\mathrm{Z}}^2) \simeq .035$. An update will be presented this summer (2000).

In the case of $(g-2)_\mu$ at E821 BNL

Both experimentally and theoretically, $a_\mu = (g-2)/2$ is known with a precision of $\sim 10^{-9}$. Theoretically, it is senstitive to large energy scales and to very high order radiative corrections. Its precision is limited by second order loop effects from the hadronic vacuum polarization. Experimentally, it is extremely sensitive to new physics.

The theoretical expression can be written as $a_\mu = a_\mu^{\mathrm{qed}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{had}}$. As in the case of α^{-1}, the hadronic contribution has the largest uncertainty. Today's theoretical calculation gives $a_\mu(SM) = (116\ 591\ 594.7 \pm 70) \times 10^{-11}$ []. Experimentally, a_μ is being measured at BNL by the E821 $g-2$ experiment. A 3.1 GeV π beam from the Alternating Gradient Synchrotron is used. The E821 goal is to achieve a precision of $\pm 40 \times 10^{-11}$. The present day world average on a_μ is $(116\ 592\ 050 \pm 450) \times 10^{-11}$.

The polarized muons from the decay $\pi \rightarrow \mu$ move in a uniform $\vec{B}$ field which is $\perp$ to the muon spin $\vec{s}_\mu$ and to the orbit plane. A quadrupole electric field $\vec{E}$ is used for vertical focusing. The spin precession ω_s minus the cyclotron frequency ω_c is given by $\vec{\omega}_a = -(\mathrm{e}/m)\{a_\mu \vec{B} - [a_\mu - 1/(\gamma^2 - 1)]\vec{\beta} \times \vec{E}\}$. The second term in the brace cancels out for muons with the *magic* $\gamma_\mu = 29.3 \rightarrow p_\mu = 3.01$ GeV. This is exactly the energy chosen for the experiment. The decay time spectrum of the positrons from the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ is given by $N_0 e^{-t/\gamma\tau}[1 + A(E)cos(\omega_a t + \phi(E))]$. One counts the number of positrons versus time and fits the above relation to extract ω_a.

Any deviation from the SM prediction could be interpreted as new physics e.g. muon sub structure, W compositeness, SuperSymmetry.

Atomic Parity Violation in Cesium

The atom is not a purely electromagnetic system. Parity violation can occur inside the atom. In order to detect this violation, the atoms in a gas are first given a preferential handedness e.g.right. Some suitable property is measured. The handedness is then reversed e.g.left, and the property is measured again. If the results of the two measurements differ, then parity is violated. The left-right asymmetry is expressed as $A_{LR} \propto Z^3/m_{\mathrm{Z}}^2$, where Z in the numerator is the number

of protons in the atom. The asymmetry is very small due to the large Z mass in the denominator. Cesium (Cs) 55 has been chosen because it has a reliable atomic structure calculation, it has one electron in its outer shell, and the remaining 54 electrons are tightly bound around the nucleus. Cs is the simplest of the heavy atoms, and the heaviest of the simplest.

In the Boulder experiment [], a Cs beam passes through a region of perpendicular electric, magnetic and laser fields. The highly forbidden 6S→7S transition occurs in the Cs as the weak Parity Non Conserving (PNC) transition with a probability of 10^{-11}. An electric field provokes a Stark induced transition which has a probability 10^5 times larger than the PNC transition and which can interfere with it. In order to have non zero interference between the two, the 6S→7S transition is excited with an elliptically polarized laser field. The handedness of the region is changed by reversing each of the field directions. The parity violation is apparent as a small modulation in the 6S→7S excitation rate synchronous with all of these reversals. The modulation is related to the weak charge Q_W. The Boulder result for the weak charge of Cs is []

$$Q_W\ Cs_{55}^{133} = -72.06 \pm .28_{expt} \pm .34_{th}$$

The SM prediction is given by the relation [] $Q_W^{\rm SM} = -72.72 \pm .13 - 102\epsilon_3^{rad} + \delta_N Q_W$ where $\delta_N Q_W$ indicates new physics, and $\epsilon_3^{\rm rad}$ are the radiative corrections which are evaluated to be $(4.9 \pm 1) \cdot 10^{-3}$ from high energy data results. Using this SM prediction and the experimental result, one finds $Q_W^{expt} - Q_W^{SM} = 1.18 \pm .46$ or $0.28 \leq \delta_N Q_W \leq 2.08$ at 95% C.L. , which corresponds to a 2.6σ discrepency with the SM. This result can be interpreted in the context of contact interations, as a measurement of $\Lambda_{\rm LL}$ and $\Lambda_{\rm RR}$: $12.1 \leq \Lambda^+_{\rm LL,RR} \leq 32.9$ TeV. The LEPII fermion pair cross section and asymmetry measurements exclude the regions of $\Lambda^+_{\rm RR} < 12.3$ TeV and $\Lambda^+_{\rm LL} < 12.8$ TeV.

HOW FIT IS THE STANDARD MODEL

Z Universality tests, fermion pairs at LEPII, W production and decays, triple gauge couplings, a_μ and atomic parity violation measurements are all consistent with the SM. All are stringent tests of the SM and help to set limits on a wide range of physics scenarios.

Amongst other measurements (see Figure 3), $\sin^2\theta^\ell_{\rm eff}$, $m_{\rm W}$, $m_{\rm top}$, $\sin^2\theta_{\rm W}$ and $\alpha^{-1}(m^2_{\rm Z})$ enter in the overall electroweak fit from which the Higgs mass is extracted. The χ^2/dof of the fit is 23/15, $m_{\rm Higgs} = 67^{+60}_{-33}$ GeV and $m_{\rm Higgs} < 188$ GeV at 95% C.L. . The direct searches at LEPII give $m_{\rm Higgs} > 107.7\ GeV$ at 95% C.L. [].

The weak mixing angle ($\sin^2\theta^\ell_{\rm eff} = .23149 \pm .00017$) is the strongest constraint on the Higgs mass today []. $m_{\rm W}$ would be in the race if its error were ∼25 MeV. The W mass measurement confirms the existence of the weak radiative corrections to $\sim 7\sigma$. Reducing the error on $\alpha^{-1}(m^2_{\rm Z})$ will make the $\sin^2\theta^\ell_{\rm eff}$ measurement an even stronger constraint on the Higgs mass. The same can be said about the top

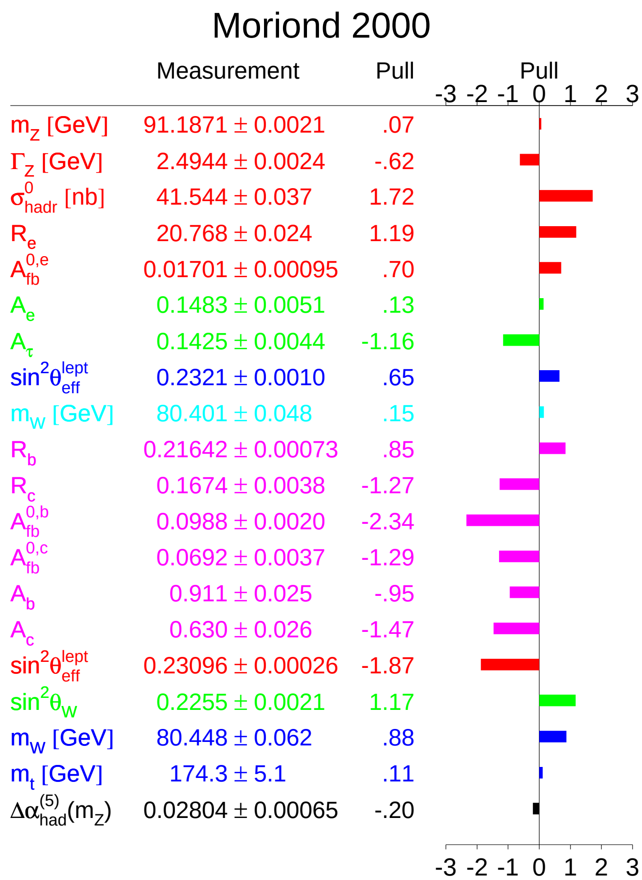

FIGURE 3. List of measurements entering the spring 2000 electroweak fit and pulls with respect to the SM prediction.

mass error with respect to the W mass measurement as a constraint on the Higgs mass.

FUTURE PROSPECTS

By the end of LEPII, each experiment will have accumulated well over 500 pb^{-1}. A realistic goal for the W mass measurement is to attain a world average error of 25 MeV, and a factor of two improvement on the TGCs. The goal of the E821 $g-2$ experiment is to reach an error on a_μ of 40×10^{-11}. New measurements of $R(s)$ for $\sqrt{s} = 0.3$ to 5.0 GeV at BESII and in Novosibirsk will help to reduce the error on α^{-1}, such that it will most likely reach $\Delta\alpha^{-1} \sim .02$.

In the near future (2001), Tevatron will start RUNII. During the four years of data taking, more than 14 fb^{-1} per experiment are expected at $\sqrt{s} = 2$ TeV. The top mass error will come down to 2-3 GeV per experiment, the overall Tevatron W mass error will be 20-40 MeV. Approximately 20 fb^{-1} will be needed for a 3σ

discovery of a SM Higgs of $m_{\text{Higgs}} < 180\ GeV$ [].

In the far future, each LHC (ATLAS and CMS) experiment will accumulate about 300 fb^{-1} over the ten years of running at $\sqrt{s} = 14$ TeV. The LHC combined experiments top mass error will be of the order of 2 GeV, the W mass error will be ≤ 25 MeV per experiment. Approximately 30 fb^{-1} will be needed for a 5σ discovery of a SM Higgs of $m_{\text{Higgs}} < 1000\ GeV$ [].

CONCLUSION

The SM is in good shape. Nothing really anomalous has been observed. A beautiful future exists for stringent tests e.g. fermion pair production, TGCs, a_μ and atomic parity violation. The same can be said about precision measurements constraining the Higgs mass e.g. at LEPII, Tevatron and LHC. There are many good reasons to be optimistic about the future of precision electroweak measurements !!

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